

Prompt X-ray and Optical Excess Emission due to Hadronic Cascades in Gamma-Ray Bursts

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ABSTRACT

A fraction of gamma-ray bursts exhibit distinct spectral features in their prompt emission below few 10s of keV that exceed simple extrapolations of the low-energy power-law portion of the Band spectral model. This is also true for the prompt optical emission observed in several bursts. Through Monte Carlo simulations, we model such low-energy spectral excess components as hadronic cascade emission initiated by photomeson interactions of ultra-high-energy protons accelerated within GRB outflows. Synchrotron radiation from the cascading, secondary electron-positron pairs can naturally reproduce the observed soft spectra in the X-ray band, and in some cases the optical spectra as well. These components can be directly related to the higher energy radiation at GeV energies due to the hadronic cascades. Depending on the spectral shape, the total energy in protons is required to be comparable to or appreciably larger than the observed total photon energy. In particular, we apply our model to the excess X-ray and GeV emission of GRB 090902B, and the bright optical emission of the “naked-eye” GRB 080319B. Besides the hard GeV components detected by *Fermi*, such X-ray or optical spectral excesses are further potential signatures of ultra-high-energy cosmic ray production in gamma-ray bursts.

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1. Introduction

Gamma-ray bursts (GRBs) are potential sources of ultra-high-energy cosmic rays (UHE-CRs, Waxman 1995; Vietri 1995; Milgrom & Usov 1996). While the required local UHECR emissivity is $\varepsilon_p^2 d\dot{N}_p/d\varepsilon_p \simeq 0.8 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$ at proton energy $\varepsilon_p \sim 10^{19} \text{ eV}$ (Waxman & Bahcall 1998; Dermer 2007), the local GRB rate may be in the range of $0.05 - 1 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (Daigne et al. 2006; Le & Dermer 2007; Guetta & Piran 2007). Assuming $p_p = 2$ for the power-law index of accelerated protons, the necessary total isotropic-equivalent energy in protons would be $E_p \sim 2 \times 10^{54} - 3 \times 10^{55} \text{ erg}$ when integrated over $\varepsilon_p \sim 10^9 - 10^{20} \text{ eV}$. Compared to the isotropic-equivalent energy released as gamma-rays, typically $E_\gamma \sim 10^{53} \text{ erg}$, this indicates that the accelerated protons must dominate the energy budget of GRBs in order for them to be viable sources of UHECRs.

Although $E_p/E_\gamma \gtrsim 10 - 100$ in GRBs may appear physically demanding, a number of considerations provide some justification (Totani 1998; Asano et al. 2009). First, in the popular internal shock model where the prompt MeV gamma-rays are attributed to synchrotron radiation from electrons accelerated in shocks within the GRB outflow (Piran 2005; Mészáros 2006), the efficiency with which the electrons are energized may be limited in comparison with the total available energy, which is the dissipated fraction of the bulk kinetic energy conveyed predominantly by protons. Since simple Coulomb collisions are ineffective in transferring the energy of the protons to the electrons within a dynamical timescale, it has been generally assumed that this can occur through some plasma instabilities with efficiencies $\epsilon_e \sim 0.1-0.5$. However, this is by no means physically guaranteed, so we are motivated to consider the possibility of proton-dominated GRBs with $\epsilon_e \ll 0.1$ and explore its consequences. Note that a high proton-to-electron ratio is not only observed in Galactic cosmic rays and inferred in supernova remnants (Aharonian et al. 2006), but also theoretically expected, at least for nonrelativistic shocks (Blandford 1994; Levinson 1996).

The prompt emission spectra of GRBs are known to be generally well described by the so-called Band model, consisting of a hard, low-energy power-law part, a softer, high-energy power-law part, and a spectral peak in between in the sub-MeV range (Band et al. 1993). However, the Large Area Telescope (LAT) onboard the Fermi Gamma-Ray Space Telescope (*Fermi*) recently detected an additional, hard spectral component above $\sim 0.1 \text{ GeV}$ in the prompt phase of the short GRB 090510 (Abdo et al. 2009b; Ackermann et al. 2010). Notwithstanding alternative models (Granot 2010; Dermer 2010), if the GRB accelerated ultra-high-energy protons with isotropic-equivalent luminosity $L_p \gtrsim 10^{55} \text{ erg/s}$, synchrotron and inverse Compton (IC) emission from an electron-positron pair cascade triggered by photopion interactions of the protons with low-energy photons (Böttcher & Dermer 1998; Gupta & Zhang 2007; Asano & Inoue 2007) can account for this GeV emission (Asano et al.

2009b).

Interestingly, in this same burst, the *Fermi* Gamma-ray Burst Monitor (GBM) observed a further, soft excess feature below ~ 20 keV, which appears to lie on a continuation of the hard, GeV power-law. A similar, even clearer X-ray excess, as well as a GeV excess was also reported for the prompt emission of the long GRB 090902B (Abdo et al. 2009c). Evidence of extra low-energy components was also reported in about ~ 15 % of BATSE bursts (Preece et al. 1996). In the optical band, several GRBs have exhibited prompt optical fluxes that are brighter than expected from simple extrapolations of their low-energy Band spectra (Yost et al. 2007; Panaitescu 2008). One of the most impressive cases was the extremely luminous optical emission of the “naked-eye” GRB 080319B (Racusin et al. 2008).

Despite alternative explanations such as an early onset of the afterglow (Ghisellini et al. 2009; Kumar & Duran 2009) or upscattering of external/photospheric photons (Toma et al. 2009, 2010; Pe’er et al. 2010), the emission from hadronic pair cascades can also potentially account for the excess components in the X-ray or even optical band, owing to the generally very wide distribution in energy of the secondary pairs and their resultant radiation. In addition to high-energy gamma-rays, prompt X-ray and optical emission may thus prove to be valuable observational signatures of UHECR acceleration in GRBs. Here we demonstrate this through Monte Carlo spectral modeling, focusing on the two remarkable cases of GRB 090902B and GRB 080319B.

2. Model and Methods

Our Monte Carlo code self-consistently calculates the photon and neutrino spectra corresponding to individual pulses in the GRB prompt emission in a one-zone approximation, including all relevant leptonic and hadronic processes (Asano et al. 2009b). More detailed descriptions of the code can be found in a series of previous publications (Asano 2005; Asano & Nagataki 2006; Asano & Inoue 2007; Asano et al. 2009). In this work, we choose not to explicitly model the MeV-range Band spectral component, whose true origin is currently under debate and may or may not be related to electrons accelerated in internal shocks. Even in the case that photospheric emission or some other mechanism is more relevant, it is plausible that coexisting internal shocks (Mészáros & Rees 2000; Toma et al. 2010; Pe’er et al. 2010) or magnetic reconnection regions (Giannios 2010) accelerate protons to ultra-high energies within the GRB outflow. Here we simply assume that a radiation field consistent with the observed Band spectrum is present within the emission region, which also contains magnetic fields with energy density U_B , and is moving out with bulk Lorentz

factor Γ at radius R from the central engine. Protons are injected in this environment with isotropic-equivalent luminosity L_p in the form of a power-law energy distribution with a high-energy cutoff, $\propto \varepsilon_p^{-2} \exp(-\varepsilon_p/\varepsilon_{p,\max})$, above $\varepsilon_{p,\min} = 10$ GeV in the comoving frame. The maximum proton energy $\varepsilon_{p,\max}$ is determined by the balance between the acceleration timescale $t_{\text{acc}} = \xi R_L/c$, where R_L is the proton gyroradius, and either the comoving expansion timescale $t_{\text{exp}} = R/(c\Gamma)$ or the proton cooling timescale t_{cool} due to synchrotron and photomeson production losses. We choose $\xi = 1$ as required for UHECR production by GRBs, and observationally inferred for supernova remnant shocks (Uchiyama et al. 2007). Of the free model parameters R , Γ , U_B and L_p , the latter two can be quantified relative to the photon energy density $U_\gamma = L_\gamma/(4\pi cR^2\Gamma^2)$ of the Band component with isotropic-equivalent luminosity L_γ as U_B/U_γ and U_p/U_γ where $U_p = L_p/(4\pi cR^2\Gamma^2)$.

The physical processes taken into account are 1) photon emission and energy losses by synchrotron radiation and Compton scattering including the Klein-Nishina regime for electrons/positrons, protons, pions and muons, 2) synchrotron self-absorption for electrons/positrons, 3) $\gamma\gamma$ pair production, 4) photomeson production for protons and neutrons, 5) Bethe-Heitler pair production ($p + \gamma \rightarrow p + e^+ + e^-$), and 6) decays of pions and muons.

For the results below, we do not include the effects of intergalactic $\gamma\gamma$ absorption due to the extragalactic background light, since the latest observational constraints (Abdo et al. 2010, and references therein) indicate that it should not be severe at the energies and redshifts of our interest here.

3. Results

3.1. GRB 090902B

GRB 090902B at $z = 1.822$ was one of the most energetic long GRBs with isotropic energy $E_{\text{iso}} = 3.6 \times 10^{54}$ erg (Abdo et al. 2009c). The detection by *Fermi* of an 11 GeV photon together with variability on timescales ~ 53 ms during the prompt phase implies a minimum bulk Lorentz factor $\Gamma_{\min} \sim 1000$. Between $T_0 + 4.6$ s and $T_0 + 9.6$ s where T_0 is the *Fermi* GBM trigger time, a hard power-law component with photon index $\Gamma_\gamma = -1.94$ was found above 0.1 GeV, in addition to a component well fit by a Band function with low-energy photon index $\alpha = 0.07$, high-energy photon index $\beta = -3.9$ and peak energy $E_{\text{peak}} = 908$ keV. This Band component manifests an atypically narrow energy distribution, as apparent in Figure 1. Also observed was a soft excess feature below 50 keV that is consistent with an extrapolation of the GeV power-law down to these energies. The gray shaded area in Figure 1 represents the 1- σ confidence region of the best-fit, unfolded spectrum for GRB 090902B,

based on a likelihood analysis of the combined GBM and LAT data under the assumption of a Band function plus an additional power-law (Abdo et al. 2009c).

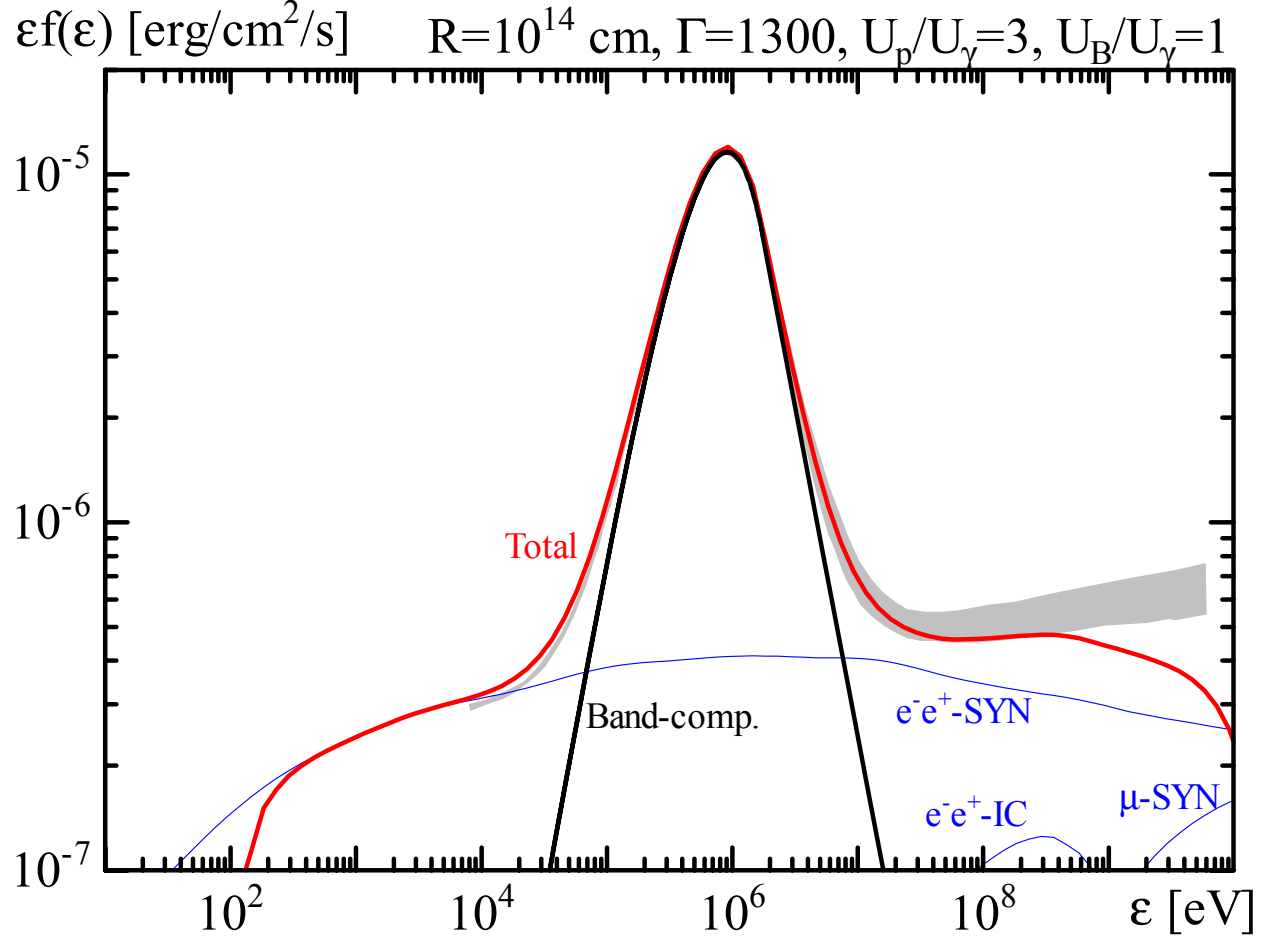


Fig. 1.— Model spectrum for parameters listed at the top as thick red curve compared with observations of GRB 090902B, for which the gray shaded area represents the 1- σ confidence region of the best-fit, unfolded spectrum for the joint *Fermi* GBM and LAT data. The best-fit Band component is shown separately as the solid black curve. Individual contributions of synchrotron and inverse Compton from secondary electron-positron pairs as well as muon synchrotron are denoted by thin blue curves as labelled, not including the effects of $\gamma\gamma$ absorption or synchrotron self-absorption.

Overlaid in Figure 1 is our model of pair cascade emission induced by ultra-high-energy protons for the parameters $R = 10^{14}$ cm, $\Gamma = 1300$, $U_p/U_\gamma = 3$, and $U_B/U_\gamma = 1$. The overall agreement is good, except for some deviation above \sim GeV. Considering the low photon statistics at the highest energies for the LAT, and the fact that the reference spectrum is an

unfolded one wherein a simple functional form was assumed, we do not consider this to be a serious discrepancy. Because the GeV component is characterized by photon index ~ -2 with relatively low power compared to the Band component, it can be reproduced reasonably well by pair cascade emission that is dominated by synchrotron processes in a relatively strong magnetic field (e.g. Coppi 1992). The necessary nonthermal proton luminosity is then not excessive and only comparable to the Band component luminosity. These inferences are in notable contrast to the case of GRB 090510, whose GeV emission was harder with photon index ~ -1.6 and more luminous, warranting a stronger inverse Compton contribution from the secondary pairs and consequently a weaker magnetic field. This entailed a lower $\varepsilon_{p,\max}$ and hence lower photopion production efficiency, leading to the requirement that $L_p > 10^{55}$ erg s $^{-1}$ (Asano et al. 2009b).

The cascade emission also extends to low energies and naturally explains the X-ray excess. Note that a proton synchrotron model would have difficulty accounting for such spectra with roughly equal power across a very broad energy range. On the other hand, for the present parameters, we do not expect strong emission down to the optical band, as the spectrum turns over at $\lesssim 100$ eV due to synchrotron self-absorption. Moreover, the narrow energy distribution of the Band component and the corresponding $\gamma\gamma$ opacity precludes the injection of electrons/positrons with energies low enough to radiate in the optical (see thin blue curve in Figure 1 where self-absorption is neglected). We also mention that the high-energy cutoff due to $\gamma\gamma$ absorption expected at $\gtrsim 10$ GeV is a diagnostic feature to be tested in future observations of similar bursts.

3.2. GRB 080319B

GRB 080319 at $z = 0.937$ was also an energetic long GRB with isotropic gamma-ray energy $E_{\text{iso}} = 1.3 \times 10^{54}$ erg. Most remarkably, it was accompanied by an extremely bright, prompt optical burst reaching 5.3 apparent magnitude, earning the moniker “naked-eye GRB”. Unlike most previous prompt optical detections that could be reasonably interpreted as emission from an external reverse or forward shock (Fox & Meszaros 2006; Roming et al. 2006; Yost et al. 2007), the unprecedentedly well-sampled light curve of this burst revealed several peaks over the first ~ 50 s that were correlated with the variability in MeV gamma-rays (Racusin et al. 2008; Stamatikos et al. 2009; Beskin et al. 2010), before switching over to a behavior more typical of afterglows. Furthermore, the early optical fluxes lie far above low-energy extrapolations of the concurrent, time-resolved Band spectra, clearly pointing to a distinct spectral component associated with the prompt phase (Racusin et al. 2008). Among different possibilities, an interpretation attributing the optical and MeV

emission respectively to the synchrotron and synchrotron-self-Compton (SSC) processes have often been invoked (e.g. Racusin et al. 2008).

For comparison with our hadronic cascade model, we focus on the time interval between $T_0 + 12$ s and $T_0 + 22$ s where T_0 is the Swift/BAT trigger time, during which the Band component reaches a maximum luminosity of 1.0×10^{53} erg s $^{-1}$. The Band parameters we adopt are $\alpha = -0.45$, $\beta = -3.5$, and $E_{\text{peak}} = 748$ keV, noting that β is only constrained by the data to be $\beta < -3.412$. Figure 2 illustrates our results for the parameters $R = 10^{16}$ cm, $\Gamma = 1000$, $U_p/U_\gamma = 45$, and $U_B/U_\gamma = 3$.

Synchrotron emission from the pair cascade softens the spectrum below ~ 100 keV so that the low-energy slope of the Band component becomes concordant with the observed value of $\alpha = -0.816$. The cascade emission continues down into the optical band with some curvature and accounts well for the observed optical intensity as long as synchrotron self-absorption does not set in, which necessitates $\Gamma > 1000$ and $R > 10^{16}$ cm. Such large values for Γ and R imply a relatively low comoving photon density and thus low photopion production efficiency, which scales as $\propto R^{-1}\Gamma^{-2}$. This in turn calls for a proton luminosity $L_p \sim 10^{55}$ ergs $^{-1}$, strongly dominating that in the Band component. Note that a substantially larger energy budget than in MeV gamma-rays alone is also unavoidable in the SSC model for GRB 080319B due to luminous, second-order IC emission in the GeV band (Racusin et al. 2008).

Occurring before the launch of *Fermi*, the GeV properties of GRB 080319B remains largely unknown. Upper limits at the level of $\sim 10^{-5}$ erg cm $^{-2}$ s $^{-1}$ above 10 GeV were obtained by MILAGRO (Aune 2010). This does not contradict the high-energy component expected in our model, consisting of synchrotron emission from secondary pairs with luminosity $\sim 0.1L_\gamma$ and photon index ~ -2 , extending up to a cutoff ~ 100 GeV due to internal $\gamma\gamma$ -absorption (Figure 2). The spectral shape is conspicuously different from the sharply peaked one expected from second-order IC emission in the SSC interpretation (Racusin et al. 2008), providing an important distinguishing feature for UHECR-induced emission components. The overall similarity of our model spectrum for GRB 080913B with that of GRB 090902B also encourages us to search for optical signatures in future *Fermi* GRBs.

4. Conclusions and Discussion

Emission from pair cascades initiated by photopion production of ultra-high-energy protons in GRB outflows can yield spectra with roughly equal power over a broad energy

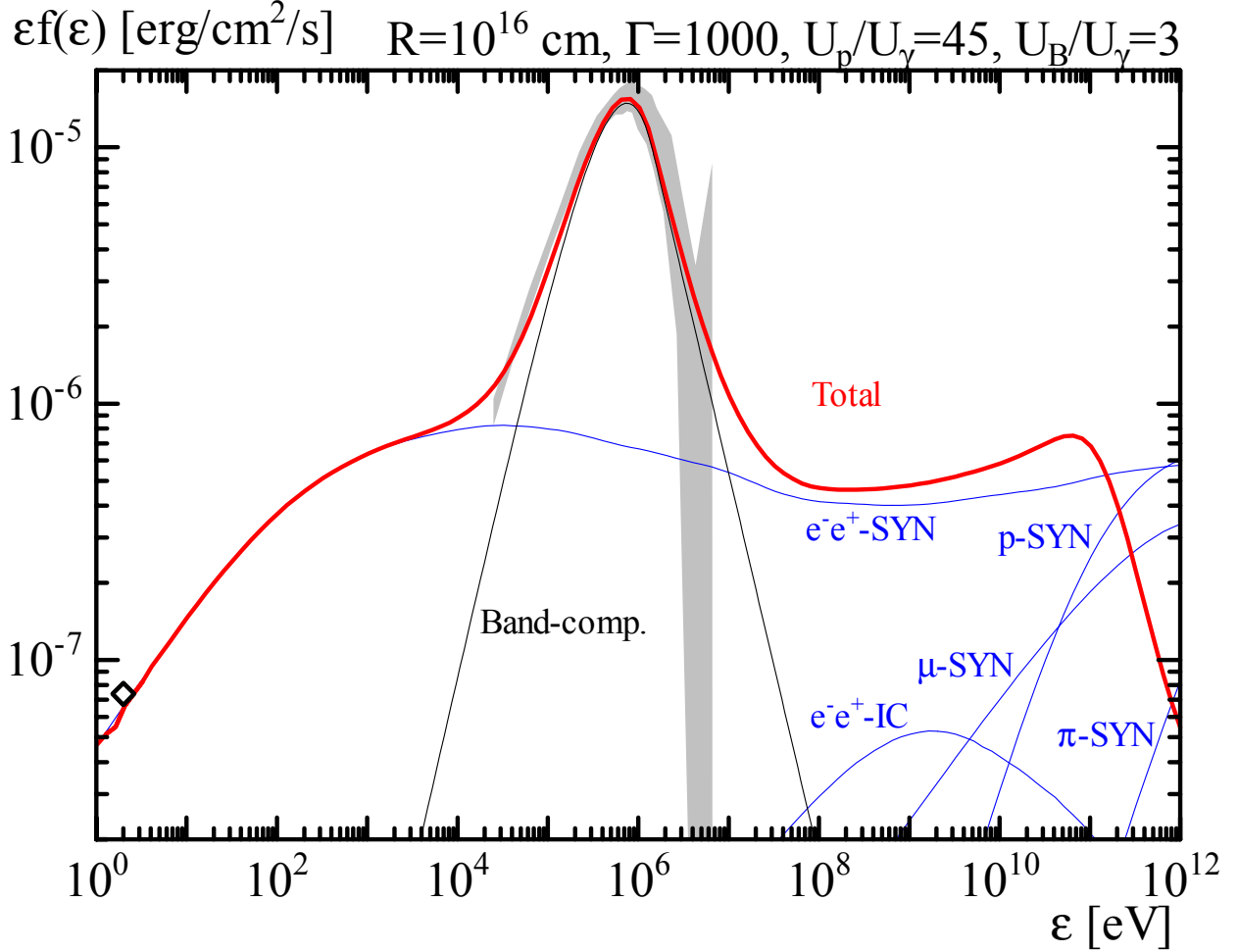


Fig. 2.— Model spectrum for parameters listed at the top as thick red curve compared with observations of GRB 080319B, for which the gray shaded area represents the spectrum measured between $T_0 + 12$ s and $T_0 + 22$ s by Swift/BAT and Konus-Wind. The contemporaneous optical flux observed by “Pi of the Sky” is the black diamond. The best-fit Band component is shown separately as the thin black curve. Individual contributions of synchrotron and inverse Compton from secondary electron-positron pairs, as well as muon synchrotron and proton synchrotron are denoted by thin blue curves as labelled, not including the effects of $\gamma\gamma$ absorption or synchrotron self-absorption.

range. While GeV-TeV signatures due to hadronic processes have been discussed previously by many authors (e.g. Dermer 2010), the relevance of associated X-ray or optical features had not received much attention. Here we showed that synchrotron emission from hadronic cascades can reproduce the excess X-ray and GeV components in GRB 090902B, as well as the bright optical emission in GRB 080319B. Unlike the case of GRB 090510, the necessary

proton luminosity for GRB 090902B is only comparable to the observed photon luminosity. On the other hand, GRB 080319B calls for an isotropic-equivalent proton luminosity $L_p \sim 10^{55} \text{ erg s}^{-1}$, which may appear extreme but is in fact consistent with the energetics requirements for GRBs to be the origin of UHECRs (Asano et al. 2009).

The detailed time variability properties of the low-energy excess components are not yet known observationally, except for the well-documented optical light curve of GRB 080319B (Racusin et al. 2008; Stamatikos et al. 2009; Beskin et al. 2010) (see also Vestrand et al. 2004; Blake et al. 2004). Although an in-depth discussion is beyond the scope of this paper, we may expect the variability of hadronic cascade emission to be influenced by the timescale of photopion production and thus qualitatively different from purely leptonic processes. There should also be a close connection between the excess components at low and high energies. The X-ray excess may be better characterized in the near future by the Joint Astrophysics Nascent Universe Satellite (JANUS), which will conduct prompt GRB observations including the 1-20 keV band. The continuing development of wide-field and/or rapidly-slewing telescopes (Mundell et al. 2010) should bring forth a clearer picture in the optical band for more bursts. The broadband variability of hadronic emission components will be discussed at greater length in subsequent work.

In order to explain the complex behavior of the afterglow of GRB 080319B, a two-component jet model was discussed in Racusin et al. (2008), with a narrower and faster jet dominating the early phase of the afterglow, and a wider and slower jet describing the later phase. Such composite models would loosen the constraints that we obtained here for our one-zone model. If the wider jet is the main site of proton acceleration, and if it is dense enough to cause $p - p$ collisions in the prompt phase, there may be other parameter sets that can reproduce the optical emission. Furthermore, the jet collimation-corrected energy in protons can be diminished in such a composite model.

One of the problems for the internal shock synchrotron model of the prompt emission is the difficulty in accounting for the observed low-energy spectra of the Band component, which are generally much harder than naive expectations with $\alpha = -1.5$, including the GRBs dealt with in this paper. Many authors have proposed modifications to the model (e.g. Asano & Terasawa 2009, and references therein) or alternatives such as those based on photospheric emission (e.g. Mészáros & Rees 2000). Although here we have tacitly assumed the presence of the Band component as is observed, in the future we intend to model all spectral components self-consistently within the context of physical processes that can reconcile the low-energy index observations, in order to achieve a more comprehensive understanding of emission mechanisms together with UHECR production in GRBs.

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